

University of Groningen

Atomic hydrogen produced in M33 photodissociation regions

Heiner, J. S.; Allen, R. J.; van der Kruit, P. C.

Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
[10.1111/j.1365-2966.2011.18581.x](https://doi.org/10.1111/j.1365-2966.2011.18581.x)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2011

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Heiner, J. S., Allen, R. J., & van der Kruit, P. C. (2011). Atomic hydrogen produced in M33 photodissociation regions. *Monthly Notices of the Royal Astronomical Society*, 416(1), 2-12. <https://doi.org/10.1111/j.1365-2966.2011.18581.x>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Atomic hydrogen produced in M33 photodissociation regions

J. S. Heiner,^{1,2,3*} R. J. Allen² and P. C. van der Kruit³

¹Département de Physique, Université Laval, Québec, QC G1V 0A6, Canada

²Space Telescope Science Institute, Baltimore, MD 21218, USA

³Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, the Netherlands

Accepted 2011 February 18. Received 2011 February 18; in original form 2010 November 23

ABSTRACT

We derive total (atomic + molecular) hydrogen densities in giant molecular clouds (GMCs) in the nearby spiral galaxy M33 using a method that views the atomic hydrogen near regions of recent star formation as the product of photodissociation. Far-ultraviolet (FUV) photons emanating from a nearby OB association produce a layer of atomic hydrogen on the surfaces of nearby GMCs. Our approach provides an estimate of the total hydrogen density in these GMCs from observations of the excess FUV emission that reaches the GMC from the OB association and of the excess 21-cm radio H I emission produced after these FUV photons convert H₂ into H I on the GMC surface. The method provides an alternative approach to the use of CO emission as a tracer of H₂ in GMCs and is especially sensitive to a range of densities well below the critical density for CO(1–0) emission.

We describe our ‘PDR method’ in more detail and apply it using *GALEX* FUV and Very Large Array 21-cm radio data to obtain volume densities in a selection of GMCs in the nearby spiral galaxy M33. We have also examined the sensitivity of the method to the linear resolution of the observations used; the results obtained at 20 pc are similar to those for the larger set of data at 80-pc resolution. The cloud densities we derive range from 1 to 500 cm^{−3}, with no clear dependence on the galactocentric radius; these results are generally similar to those obtained earlier in the cases of M81, M83 and M101 using the same method.

Key words: ISM: atoms – ISM: clouds – ISM: molecules – galaxies: individual: M33 – galaxies: ISM – ultraviolet: galaxies.

1 INTRODUCTION

Molecular hydrogen is the major component of the baryonic matter in the Universe, but direct observations of its large-scale distribution and motions within and between galaxies are hampered by the fact that the molecule has no dipole moment. The absorption and emission of radiation from H₂ can occur via the much weaker quadrupole coupling, but the lowest rotational transition has $E/k = 510$ K ($\lambda = 28.2\mu$) and emission therefore requires a significant heat source for excitation. Secondary tracers of H₂ include the rotational lines of the CO molecule and infrared continuum emission from the accompanying dust, but the excitation requirements of the former favour gas at relatively high density ($n \gtrsim 1000$ cm^{−3}) and the thermal radiation properties of the latter favour gas at relatively high temperature ($T_K \gtrsim 20$ K) and depend on grain characteristics. The cool ($\lesssim 10$ K), sparse ($n \lesssim 100$ cm^{−3}) component of the interstellar medium occupies a region of parameter space that is difficult to explore and its contribution to the total gas content of a galaxy remains uncertain.

In nearby galaxies, the most common indirect means of detecting molecular hydrogen is carbon monoxide (CO), tracing dense, relatively cold molecular gas. On galaxy-wide scales, CO may or may not be a good indicator of the total molecular gas content, but on the scale of individual complexes of giant molecular clouds (GMCs) the situation becomes more complicated [see e.g. Leroy et al. (2007) and Leroy et al. (2009) for CO-free H₂ envelopes in the Small Magellanic Cloud]. Langer et al. (2010) present recent observations of C II emission without CO counterparts, tracing warm H₂ gas.

Another way to trace the ‘total gas’ is through infrared dust emission (Israel 1997). Recent results from *Herschel* have greatly expanded the potential application of this approach (e.g. Braine et al. 2010).

Here we use an alternative method that is sensitive to low-density gas and is relatively insensitive to temperature. The tracer is atomic hydrogen, considered to be a result of the photodissociation of H₂ by far-ultraviolet (FUV) photons emanating from OB associations of young massive stars and impinging on the surfaces of nearby GMCs. A simple model of the photodissociation process in these photodissociation regions (PDRs) permits us to estimate the total volume density (atomic + molecular) of the GMC as a function of its

*E-mail: jonathan.heiner.1@ulaval.ca

relative dust content, the intensity of the incident FUV radiation and the column density of H I created on the cloud surface. Observations of nearby galaxies by the *GALEX* satellite provide the FUV data, the Very Large Array (VLA) radio telescope provides H I column densities from 21-cm emission and optical emission lines in the ionized gas near the OB association provide estimates of the local dust-to-gas ratio. Allen, Atherton & Tilanus (1986) presented the first evidence that the dissociation of H₂ into H I occurs on kiloparsec scales in the nearby galaxy M83, and in the meantime several nearby galaxies have been studied in more detail including M81 (Allen et al. 1997; Heiner et al. 2008a), M101 (Smith et al. 2000) and (again) M83 Heiner et al. (2008b). We will refer to this approach as the ‘PDR method’, which we describe and apply here to M33.

The nearby galaxy M33 is an obvious choice to apply the PDR method to and derive total hydrogen volume densities from it. M33 is close enough to permit resolving some of the atomic hydrogen structures around sites of recent star formation. Besides utilizing the full resolution available in the FUV and H I images (≈ 20 pc), we also apply the method at a deliberately reduced resolution (≈ 80 pc), which has the advantage of revealing more of the larger scale structure of the PDRs and allows us to compare the M33 results to our previous M81 and M83 results. The latter two galaxies are at a distance of 3.6 and 4.5 Mpc, respectively, but M33 is considerably closer, at 847 kpc (Saha et al. 2006), and therefore offers a superior linear resolution at the same angular resolution. At the same time, M33 is not too close to lose the larger scale morphology, while being reasonably face-on. The influence of resolution effects on the PDR method can also be studied this way.

Recent work on M33 has revealed the detailed distribution of molecular clouds detectable in CO emission (e.g. Rosolowsky et al. 2007; Gratier et al. 2010; Onodera et al. 2010). Metallicities of the disc of M33 have been investigated at an increasing spatial resolution (Rosolowsky & Simon 2008; Magrini et al. 2010) and Braine et al. (2010) treat the dust and gas this galaxy. To this expansive host of results, we add independent total hydrogen volume density measurements using the PDR method.

In Heiner, Allen & van der Kruit (2009), we presented the first results of applying the PDR method to M33 at high resolution. In Heiner, Allen & van der Kruit (2010), we showed how the PDR method at reduced resolution can be used to measure the power-law slope of the volume Schmidt law of star formation as originally formulated by Schmidt (using volume density instead of surface density). In this paper, we present our full PDR method results of M33 that were used in the previous two papers, at high resolution as well as reduced resolution. The aim of this work is to compare the densities with our previous M81 and M83 results and test the consistency of the PDR method at two widely different linear resolutions.

The data used as input for the PDR method and the method itself are detailed in Section 2. The total hydrogen volume densities in candidate PDRs in M33 are presented in the next section: the densities from the reduced-resolution analysis in Section 3.2 and the full-resolution results in Section 3.3. We briefly compare the results of the PDR method in M33 to those in M81 and M83 and summarize our conclusions in Section 4.

2 DATA AND METHOD

2.1 The PDR method

Determining the total hydrogen volume density in candidate PDRs requires measurements of the local radiation field, which we es-

timate from FUV photometry derived from the publicly available *GALEX* M33 image. It also requires identifying potential GMCs, traced by ‘patches’ of atomic hydrogen: distinct features of H I found near OB star clusters. We focus on FUV emission above the diffuse background radiation field and we assume that this emission causes the distinct H I features above the H I background levels. In this manner, we attempt to obtain clear and simple components to our method and keep the geometry of the candidate PDRs surrounding the OB clusters simple.

The 21-cm, 20-arcsec and 5-arcsec M33 images were provided by David Thilker & Rob Braun (private communication). The linear resolution for the reduced-resolution comparison is about 80 pc at the distance of M33, from a combination of data from the VLA (B, C and D configurations) and the GBT (for a complete explanation of the procedure, see Braun et al. 2009),¹ and the full-resolution analysis was carried out at a 5-arcsec resolution. The images are a mosaic of radio pointings that cover the extent of the *GALEX* image. At the 5-arcsec resolution, typical noise levels are $2 \times 10^{20} \text{ cm}^{-2}$.

To calculate linear distances within M33, necessary to compute incident UV fluxes, we assume this galaxy to be located at a distance of 847 kpc (Saha et al. 2006). [The same parameters were used in Heiner et al. (2009).] To deproject distances, we adopt a position angle of 23° and an inclination of 56° for its disc, from Zaritsky, Elston & Hill (1989). Its R_{25} is 28.8 arcmin, or 7.1 kpc (Vila-Costas & Edmunds 1992), which we used to normalize our galactocentric radius measurements. The radius measurements are needed to calculate the dust-to-gas ratio with the assumption of a galactic metallicity gradient. A uniform foreground extinction of $A_{\text{FUV}} = 0.33$ mag is assumed to correct the measured UV flux, using $E(B - V)$ from Schlegel, Finkbeiner & Davis (1998) and the expression for A_{FUV} from Gil de Paz et al. (2007). As in our previous papers, we ignore internal extinction, under the assumption that it is uniform, or at least acting in all directions equally in a spherical morphology, and that the distance through the disc is comparable to the separation between the UV source and the H I patch. In that idealized case, the internal extinction can be ignored, as it works equally between the UV source and the observer as between the UV source and the H I patch. The adoption of a single value for the internal extinction affects the calculated values of the total hydrogen volume densities equally. For example, if an internal extinction of 1 mag were adopted, all values of n would need to be multiplied by 2.5. We also use the *GALEX* FUV emission at 1500 Å as a proxy for the dissociating radiation at 1000 Å, assuming a locally flat spectral energy distribution (van Dishoeck & Black 1988).

The photodissociation rate is regulated by the dust content, through obscuration of FUV radiation and catalyzation of the formation of molecular hydrogen. We derive the dust-to-gas ratio, δ/δ_0 , which is normalized to the solar neighbourhood value, from the metallicity $12 + \log(\text{O}/\text{H})$ after Issa, MacLaren & Wolfendale (1990). Under this assumption, the dust-to-gas ratio is directly proportional to the metallicity $\log(\text{O}/\text{H})$. The metallicities in M33 were measured by Rosolowsky & Simon (2008) and Magrini et al. (2007). We use a solar metallicity of 8.69 from Allende Prieto, Lambert & Asplund (2001) to obtain the dust-to-gas ratio scaled to the solar neighbourhood. The dependence of the dust-to-gas ratio on the galactocentric radius R (in kpc) is

$$\log(\delta/\delta_0) = -0.027R - 0.33, \quad (1)$$

¹ Project codes for the radio data: (VLA) AT206, AT268 and (GBT) GBT02A-038.

using Rosolowsky & Simon (2008). More recently, Magrini et al. (2010) report a metallicity slope of $0.037 \text{ dex kpc}^{-1}$. However, we will keep the slope of 0.027 for consistency with our previous results.

With the full-resolution data, local metallicity measurements are sometimes available for our candidate PDRs; in these cases, we adopt an equivalent expression to that used in Heiner et al. (2009), independent of the galactocentric radius:

$$\log(\delta/\delta_0) = [12 + \log(\text{O}/\text{H})] - 8.69. \quad (2)$$

The foreground extinction that was used to correct the FUV flux is 0.33 mag , based on Schlegel et al. (1998) and Gil de Paz et al. (2007). The equation describing the photodissociation process, as derived from Sternberg (1988) and Allen (2004), is

$$N_{\text{H II}} = \frac{7.8 \times 10^{20}}{\delta/\delta_0} \ln \left[1 + \frac{106 G_0}{n} \left(\frac{\delta}{\delta_0} \right)^{-1/2} \right] \text{ cm}^{-2}. \quad (3)$$

In this form, it is a clear expression of the atomic hydrogen column density that is created by photodissociation on the surface of GMCs.

Heaton (2009) derived a somewhat improved version of this equation, requiring all derived values of n in this paper to be multiplied by $(\delta/\delta_0)^{0.2}$, which is well within our current estimated levels of uncertainty in the case of M33. We maintain the use of equation (3) at this time for consistency with our results in Heiner et al. (2009) and Heiner et al. (2010).

We considered the overall H I distribution across the disc of M33 and adopted a background H I column density of $1.2 \times 10^{20} \text{ cm}^{-2}$ inside $1.1 R_{25}$ and $0.5 \times 10^{20} \text{ cm}^{-2}$ outside this radius. We do this in an attempt to isolate the additional H I produced by photodissociation under the influence of the nearby OB associations. We checked the reduced-resolution background levels of the H I column densities throughout M33 and chose to characterize the trend with these two values. They have a very small impact on the final results as long as they are only a fraction of the 7.8×10^{20} scaling in the exponential of the model when computing the total hydrogen volume density n . We measured the distances between the central UV source and nearby H I ‘patches’, which are defined as a local maximum in the H I column density, and recorded their column densities out to a separation of 400 pc , the approximate maximum size of the candidate PDRs. This value is somewhat arbitrary and based on the H I morphology surrounding the central UV source. In Heiner et al. (2008a), we used 600 pc , although almost all measured values were below 400 pc . In Heiner et al. (2008b), we used 480 pc . Erroneously including H I patches that are not produced under the influence of the assumed central UV source results in low computed total hydrogen volume densities.

We censored background-subtracted column densities below $0.5 \times 10^{20} \text{ cm}^{-2}$. As an example of the resolution of the data and the scale of the candidate PDRs, we show NGC 604 in Fig. 1. The H I contours illustrate the morphology of atomic hydrogen surrounding the central concentration of O and B stars in NGC 604, the brightest H II region in M33. While this region has been studied in much more detail (at a much higher resolution), it is important in the context of large-scale PDRs to view this region in its entirety and to get global gas density estimates from it. In the full-resolution H I data, we measured individual local H I column density backgrounds based on the average H I column density near the candidate PDRs. These background levels will be listed for every region in the full-resolution results.

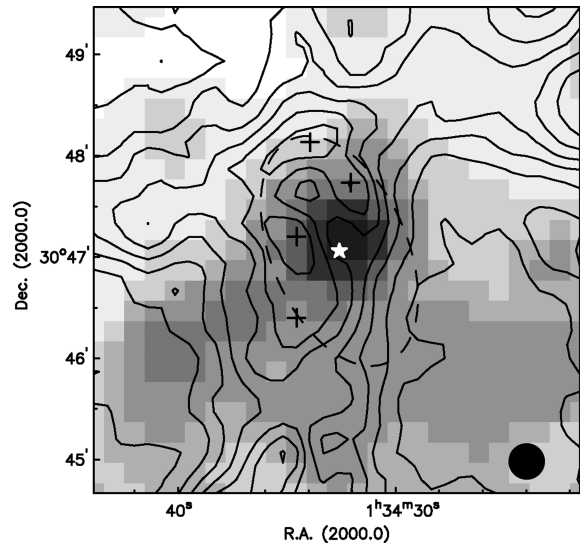


Figure 1. Example: NGC 604 seen as a large candidate PDR. Grey-scale levels (FUV counts per second per pixel) are 0.25, 0.5, 0.75, 1, 2.5, 5, 7.5, 10, 25 and 50. The fitted centre of the UV emission is marked with a white star. The H I contour levels are (in 10^{21} cm^{-2}) 0.5, 1, 1.5, 2 and 2.5. Measured H I patches are indicated with the black crosses. The dashed ellipse is an example of how $\rho_{\text{H II}}$ was measured – namely deprojected using M33’s position angle and inclination. Its major-axis has a radius of about 280 pc . A 20-arcsec beam is drawn in the lower right-hand panel.

2.2 Improvements to the PDR method

The full-resolution images allow for a slight improvement to the PDR method. Resolved UV sources are measured independently (although they are still expected to harbour a certain number of O and B stars each) and their incident flux G_0 on individual H I patches is summed to derive a cumulative G_0 . We did not consider whether one UV source blocks another in the direction of an H I patch, since we could not deproject the three-dimensional structure of these OB clusters from the FUV image. It can, however, be assumed that this is not a big issue if the extinction close to these sources is low.

Another improvement to the method is the use of locally measured metallicity values where available (equation 2). Otherwise, we use the single metallicity gradient equation for M33 (equation 1). As in M81 and M83, we did not aim for a complete sample of candidate PDRs in M33, but rather we selected those regions that stood out in their FUV emission and had a morphology that seemed to indicate the presence of large-scale PDRs. The latter merely means that we preferred regions with a relatively simple apparent H I morphology. We selected regions with a progressively more (apparent) complex H I structure. Additionally, when a larger, resolved H I structure appeared to be present in a candidate PDR, we measured its average column density and calculated a global total hydrogen volume density. This is similar to the method used in M81 and M83, except that in M33 the structures are resolved. We explicitly assume that a large-scale PDR with a shell of H I is observed in these cases, with a radius of up to a few hundred parsecs. NGC 595 is an example where this morphology is particularly obvious.

In addition to the UV-selected candidate PDRs, we included a few regions that had either individual CO detections associated to it, from Engargiola et al. (2003), or individual metallicity measurements. Almost all of these candidate PDRs, primarily selected by FUV emission, are previously catalogued H II regions. The ones starting with BCLMP derive their names from Boulesteix et al. (1974). The ones starting with CPSDP come from Courtes et al.

(1987). Our sample includes one region that has no name at this time, which we will refer to as ‘Region 42’, consistent with the numbering of the reduced-resolution results.

3 RESULTS

3.1 Source selection

The candidate PDRs that were selected for our analysis are shown in Fig. 2. We selected 42 prominent FUV sources in M33 at reduced resolution, while attempting to cover the full range of galactocentric radii available to us. Each UV-selected region has multiple measured H I patches, providing a range of total hydrogen volume density measurements per candidate PDR. Note that we did not aim to identify all candidate PDRs, as source completeness was not our goal.

At the full resolution, we selected 10 regions. At this level of detail, the larger scale (a few hundred parsecs) morphology of H I is resolved into smaller scale (several tens of parsecs) H I features. It is important to see if the results of the PDR method change when applying it at full resolution. We also wanted to take advantage of the availability of individual dust-to-gas ratio measurements. Finally, some regions also had measurements of CO available, so the resulting cloud densities can be compared to CO results. At the same time, we tried to preserve the spread in galactocentric radius coverage.

The full-resolution H I morphology is considerably more detailed, and identifying clear H I patches is not as easy as in the reduced-resolution case. Therefore, we selected a limited subset of the regions featured in the reduced-resolution analysis and studied them more extensively. The full-resolution regions are chosen with several criteria in mind: apparent presence of a large-scale H I (partial) shell, known as H II regions (e.g. NGC 604), availability of individual metallicity data and availability of CO measurements, while still keeping a representative spread in the galactocentric radius. The final sample included 10 regions. Eight of these are also present in the reduced-resolution sample, one is an H II region close to a reduced-resolution region and one does not appear in the reduced-resolution

analysis. These 10 regions feature a rich and detailed morphology, while at the same time the resulting total hydrogen volume densities are shown not to differ significantly from the reduced-resolution analysis result (see Section 4.1).

3.2 Cloud densities in M33, reduced density

Two example overlays of M33 candidate PDRs (locations are marked in Fig. 2) at reduced resolution are shown in Fig. 3. A full set of overlaid plots, Figs 10–15, can be found in the online version of this article (see Supporting Information).

The FUV fluxes of the central sources in our candidate PDRs are displayed in Fig. 4(a) and listed in Table 1 along with their locations and the aperture used to measure the FUV flux and the galactocentric radius of each source.

A gradual decline in maximum values can be seen going outwards. A similar decline can be seen in the minimum values, but we suspect that crowding effects are possible here, leading us to miss the fainter sources. We are assuming that the maximum values are real and not a selection effect, whereas a sensitivity limit has been reached at larger galactocentric radii. The fluxes show the same spread as we reported for M83 (Heiner et al. 2008b) – namely 2 dex or less at any given galactocentric radius. Since associations of O and B stars are measured, the number of those stars per cluster could decrease with the radius, causing the general decline. On an absolute scale, the difference in flux values is caused only by the different distances of M83 and M33 (the luminosities of the UV sources are in the same range).

The measurements of the candidate PDRs are shown in Fig. 4 and in Table 2. The figure and table show the measured H I column densities of candidate PDRs, the separation between the OB clusters and associated H I patches, the calculated incident flux G_0 and finally the derived total hydrogen volume densities.

Fig. 4(b) shows the H I column densities of the patches found near each of the UV sources. The patches are local maxima in the column densities that are assumed to be caused by H I produced in a PDR. Each UV source can have multiple H I patches associated to it. The measured H I columns are fairly flat out to a radius of $0.8R_{25}$

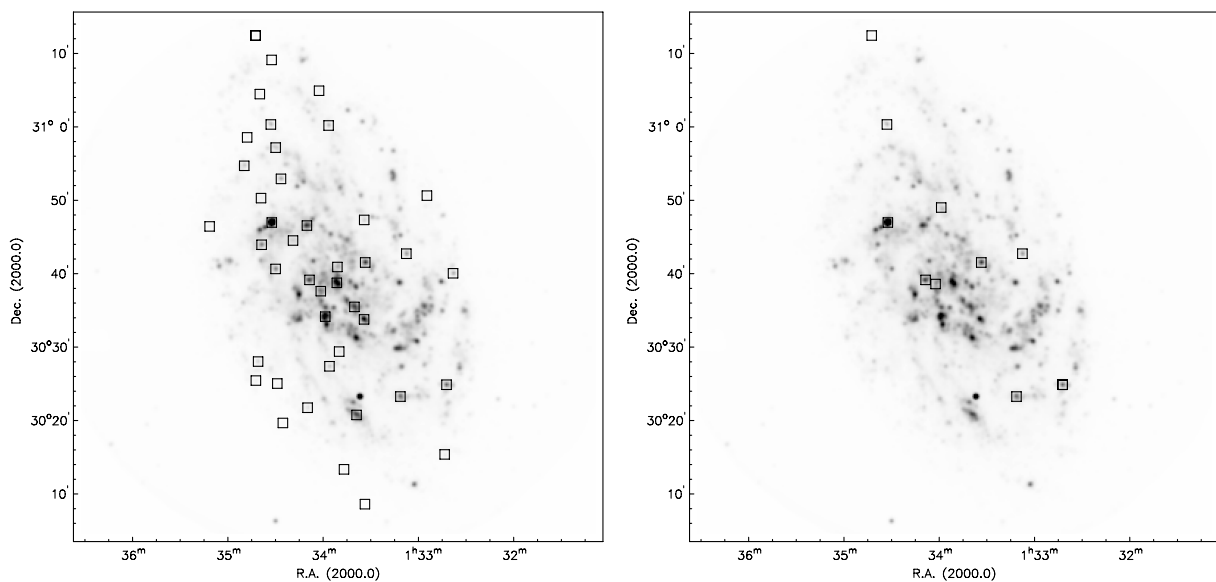
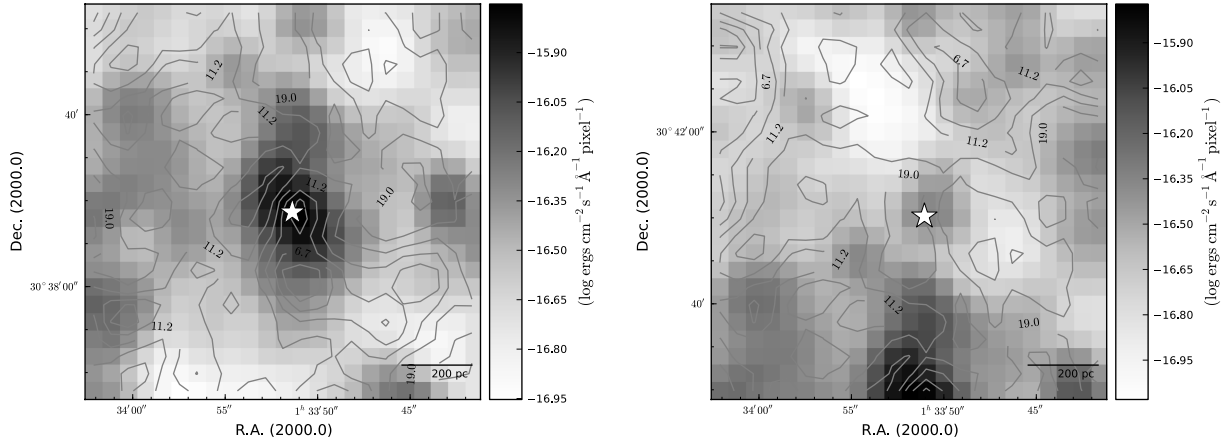


Figure 2. Candidate PDR locations are indicated with boxes on this *GALEX* FUV image (smoothed to 30 arcsec). The candidate PDRs were selected on the basis of their FUV emission. Left-hand panel: reduced-resolution regions. Right-hand panel: full-resolution regions.



1 2

Figure 3. M33 candidate PDRs at reduced resolution (the full set is available in the online version of this article – see Supporting Information). The H I column density contours are plotted against a background of the FUV flux in grey-scale. The fitted position of the central UV complex is marked by a star. A distance scale is indicated, but see Fig. 1 for how we deproject the distances. The integrated FUV fluxes can be found in Table 6 (see Supporting Information).

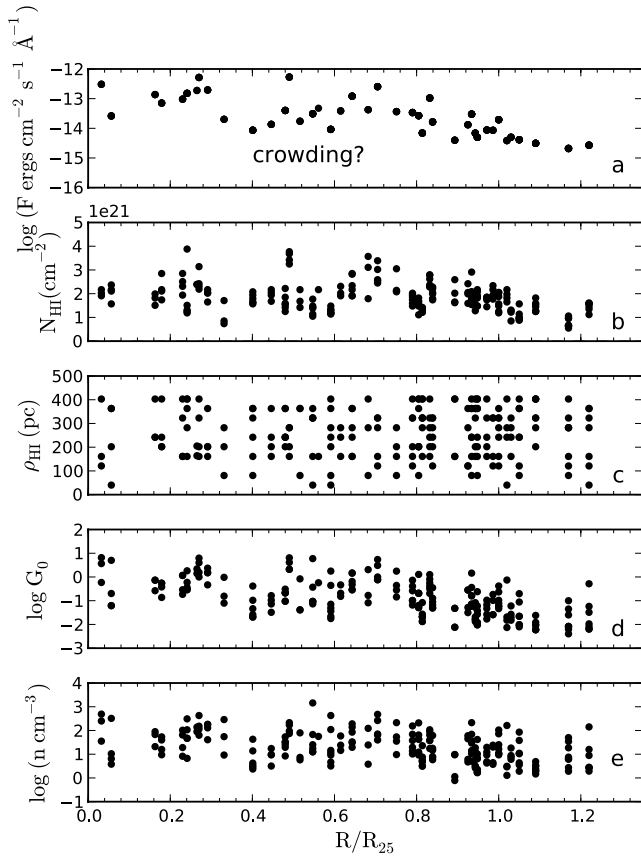


Figure 4. Combined results are plotted here as a function of the normalized galactocentric radius. Panel (a): FUV fluxes of the candidate PDRs, not corrected for extinction. Panel (b): H I column densities associated with the central UV sources. Panel (c): $\rho_{\text{H I}}$, the separation between the central UV source and each H I patch. Panel (d): incident flux G_0 on each H I patch. Panel (e): total hydrogen volume densities $n = n_{\text{H I}} + 2n_{\text{H}_2}$.

(with some spread), after which they start to decline. The maximum measured column densities are affected by beam smoothing and related to the linear resolution.

Using the measured separation between the central UV source in each candidate PDR and its associated H I patches ($\rho_{\text{H I}}$, Fig. 4c),

Table 1. Locations and FUV fluxes of candidate PDRs. This is an example of the full table, Table 5, which is available in the online version of this article (see Supporting Information).

Source number	RA (J2000) (^h ^m ^s)	Dec. (J2000) ([°] ['] ^{''})	Radius (kpc)	F_{FUV}^a	Aperture (arcsec)
1	1 33 51.371	30 38 52.01	0.23	305.35	96
2	1 33 51.052	30 41 1.18	0.40	26.08	36
3	1 33 40.271	30 35 34.72	1.16	137.22	72
4	1 34 1.540	30 37 43.83	1.27	71.03	60
5	1 34 8.658	30 39 15.42	1.63	96.25	72
6	1 33 34.135	30 33 53.24	1.71	151.01	72
7	1 33 33.401	30 41 37.88	1.88	188.70	156
8	1 33 58.709	30 34 14.98	1.92	518.50	156
9	1 34 10.340	30 46 39.52	2.06	195.81	108
10	1 34 19.129	30 44 37.26	2.35	20.08	48

^a $10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$.

Table 2. Results. This is an example of the full table, Table 6, which is available in the online version of this article (see Supporting Information).

Source number	$\rho_{\text{H I}}$ (pc)	$N_{\text{H I}}$ (10^{21} cm^{-2})	G_0	G/G_{bg}	n (cm^{-3})	a
1a	121	1.91	6.53	8.01	487	0.60
1b	161	2.02	3.67	4.51	249	0.59
1c	403	2.17	0.59	0.72	35	0.58
2a	40	2.11	5.02	8.18	323	0.97
2b	202	2.37	0.20	0.33	10	0.61
2c	363	1.57	0.06	0.10	6	0.52
2d	363	2.17	0.06	0.10	4	0.58
3a	242	1.82	0.73	0.81	67	0.54
3b	242	1.51	0.73	0.81	89	0.51
3c	403	1.99	0.26	0.29	21	0.55

^a Fractional error.

the incident flux G_0 on every patch is calculated and plotted in Fig. 4(d). The distribution of G_0 values is mostly flat out to a radius of $0.8R_{25}$ and after that the values start to decline due to the decreasing measured FUV fluxes. The distribution of measured separations $\rho_{\text{H I}}$ does not change with the galactocentric radius and shows no preferred value.

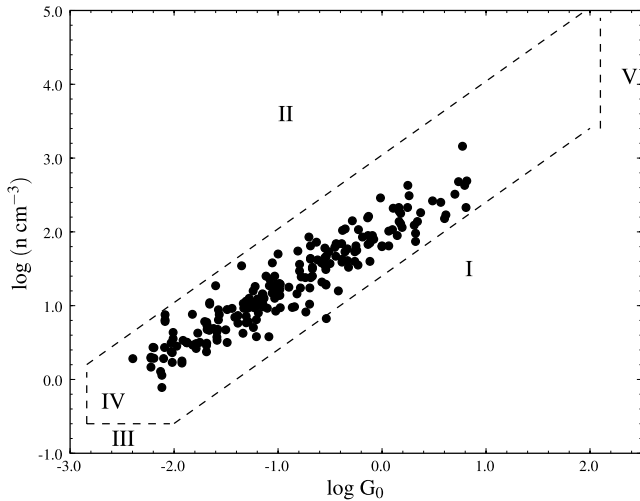


Figure 5. Observational limits are marked in this plot of G_0 versus n . The roman numerals are explained in the text.

Finally, we calculate the total hydrogen volume densities n , which are plotted in Fig. 4(e), using equation (3). Values range from 1 to 500 cm^{-3} with values going up to 2500 cm^{-3} and do not change significantly with the galactocentric radius. This corresponds to H_2 densities of up to 250 cm^{-3} in GMCs across M33. A hint of an upturn at large galactocentric radii may be caused by overestimating the dust content and is not significant.

It is also instructive to plot the relation between G_0 and n , as displayed in Fig. 5, because of the selection effects, marked by the dashed lines:

I. H I column density upper limit of $5 \times 10^{21} \text{ cm}^{-2}$ at a characteristic δ/δ_0 of 0.33.

II. H I column density lower limit of $6 \times 10^{19} \text{ cm}^{-2}$ at a characteristic δ/δ_0 of 0.25. Note, however, that this lower limit can be higher in practice, as it also depends on our ability to discern H I patches against the general H I background.

III. Lowest observable n of 0.2 cm^{-3} related to the radio beam size and the H I lower limit.

IV. Minimum usable G_0 of 1.4×10^{-3} , depending on the maximum accepted size of candidate PDRs and the lowest accepted UV flux.

V. Maximum G_0 obtainable by the PDR method, considering our data of M33 of 1.2×10^2 .

Clearly, the selection effects limit the possible values of G_0 and n .

3.3 Cloud densities in M33, full resolution

We will now present the cloud densities in candidate PDRs as derived with the PDR method from the full-resolution ($\sim 20 \text{ pc}$ linear-resolution) data. These are mostly a subset of the regions selected for the reduced-resolution analysis. The corresponding regions are listed in Table 3. We will give a short description of each region, accompanied by an overlaid plot, a finding chart and a data table. The colour plots, finding charts and data tables are available in the online version of this article (see Supporting Information). An example plot, finding chart and table are shown for CPSDP 0087g in Fig. 6 and Table 4. The results for the regions NGC 604 and CPSDP Z204 are included for completeness, but were presented previously in Heiner et al. (2009). Finally, the results are gathered in a couple of

Table 3. Candidate PDRs, full resolution.

Name	Reduced-resolution number
CPSDP Z204	5
CPSDP 0087g	Near 5
BCLMP 0695	None
BCLMP 0650	24
BCLMP 0288	19
BCLMP 0269	27
NGC 604	14
NGC 595	7
BCLMP 0256	20
Region 42	42

consolidated plots. An overview plot of the location of the regions that were investigated is shown in Fig. 2.

CPSDP 0087g: We measured fluxes in a string of UV sources that seems to be surrounded by H I emission. (Fig. 16; Table 7). The H I morphology is clumpy and is mostly located to the east of the UV sources. This region has CO detections that are not directly coinciding with measured H I patches. The CO detection close to one of the UV sources is likely to arise from high temperatures. The metallicity in this region is relatively high, higher than, for example, that for CPSDP Z204 nearby. This depresses the total hydrogen volume densities in the PDR model.

CPSDP Z204 is about 1.6 kpc away from the centre of M33 and is shown in Fig. 17 and Table 8. It was described in more detail in Heiner et al. (2009) and shows a morphology of H I patches surrounding a complex of UV sources, making these H I clumps candidate PDRs. The detection of CO is a further confirmation of the presence of GMCs in the area.

NGC 595 is M33's second-brightest H II region and has been studied extensively. Wilson & Scoville (1992) studied the molecular content of this region and found it to have less molecular gas mass than NGC 604 by about an order of magnitude (half a million solar masses). They noted a significant atomic mass component and pointed to photodissociation as the likely cause of this H II . Lagrois & Joncas (2009) derive an overall electron density of the nebula of 162 cm^{-3} from $\text{H}\alpha$, $[\text{O III}]$ and $[\text{S II}]$ kinematic observations. The finding chart in Fig. 18 shows that H I patch number 1, which was selected because it has CO associated to it, has a density of 105 cm^{-3} (Table 9). However, patch number 2 is associated with CO emission as well, but has a lower density (only 12 cm^{-3}). The CO emission here may be the result of a higher temperature of the gas rather than a higher density of the GMCs. A larger scale measurement (green polygon in the overlay) yields a slightly higher density of 45 cm^{-3} .

BCLMP 0695: No clear large-scale structure can be discerned in this H II region, although the distribution of atomic hydrogen seems to suggest some filamentary structures. The UV fluxes are comparable to the lower fluxes in NGC 595 and the number of sources points to a lot of recent star formation (Fig. 19; Table 10). The UV sources surround the single detection of CO in this region, and so do the H I patches. The closest ones are patch number 1 (23 cm^{-3}) and number 4 (116 cm^{-3}). We would also expect CO emission at patch number 2, since it has a density of 195 cm^{-3} , but it is also close enough to the UV source that any CO would have been broken up. In that case, it would be of interest to look for ionized carbon atoms.

NGC 604 is the largest and most luminous H II region in M33. Our measurements of NGC 604 are listed in Table 11. A detailed view of NGC 604 is shown in Fig. 20. The central cluster of OB

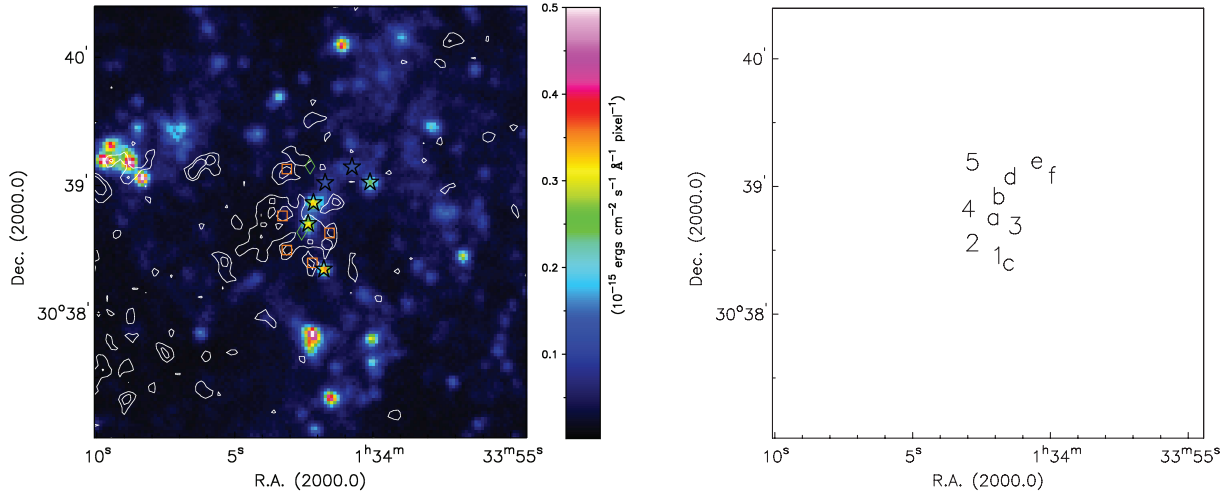


Figure 6. Left-hand panel: CPSDP 0087g region at full resolution. The FUV image is overlaid with H I contours (colour image available in the online version of this article). The H I contours are 3 and $4 \times 10^{21} \text{ cm}^{-2}$ only to emphasize the morphology of the H I peaks. The black stars mark the locations where the FUV fluxes were measured. The orange boxes are the locations of the measured H I patches. The green diamonds denote the location of CO detections by Engargiola et al. (2003). Part of CPSDP Z204 can be seen in the eastern part of the image. Right-hand panel: finding chart of the same region with letters (UV sources) and numbers (H I patches).

Table 4. Detailed measurements of CPSDP 0087g.

R_{gal} (kpc)	1.05
δ/δ_0	0.65
FUV sources (J2000)	$1^{\text{h}}34^{\text{m}}2^{\text{s}}.363 \ 30^{\circ}38'42''.30^{\text{a}}$, $1^{\text{h}}34^{\text{m}}2^{\text{s}}.175 \ 30^{\circ}38'52''.13^{\text{b}}$, $1^{\text{h}}34^{\text{m}}1^{\text{s}}.792 \ 30^{\circ}38'20''.99^{\text{c}}$, $1^{\text{h}}34^{\text{m}}1^{\text{s}}.754 \ 30^{\circ}39'01''.48^{\text{d}}$, $1^{\text{h}}34^{\text{m}}0^{\text{s}}.781 \ 30^{\circ}39'08''.93^{\text{e}}$, $1^{\text{h}}34^{\text{m}}0^{\text{s}}.127 \ 30^{\circ}39'01''.85^{\text{f}}$
FUV fluxes ($10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$)	4.55^{a} , 4.68^{b} , 4.55^{c} , 1.56^{d} , 1.65^{e} , 4.72^{f}
N_{bg} (10^{21} cm^{-2})	0.96
$N_{\text{H I}}$ (10^{21} cm^{-2})	$3.37^{1,abcd}$, $4.10^{2,abc}$, $3.67^{3,abcdef}$, $4.63^{4,abcd}$, $3.64^{5,abcd}$
G_0 (cumulative)	1.69^1 , 0.32^2 , 0.97^3 , 0.48^4 , 0.37^5
G/G_{bg} range	$0.01\text{--}1.77^1$, $0.03\text{--}0.17^2$, $0.01\text{--}0.23^3$, $0.01\text{--}0.16^4$, $0.02\text{--}0.09^5$
n (derived, in cm^{-3})	15^1 , 1^2 , 6^3 , 1^4 , 3^5
Fractional error range	0.35–0.45

stars is situated on the edge of an H I arm. We attempted to get a global measurement using an average H I column density measured on the H I arm. H I column densities to the west of NGC 604 drop to below the sensitivity limit, although a diffuse component shows on single-dish GBT data (Thilker, private communication). Since the UV emission does not particularly follow the H I arm, this faint H I emission deserves further attention.

Region BCLMP 0288 only features a morphology that suggests a large-scale PDR, which makes it an interesting target in its own right. The central cluster is embedded in H I emission that does not show discernible structure on a smaller scale. The highest H I columns go around BCLMP 0228 on the eastern side and we used an average along that ridge for our measurements (Fig. 21 and Table 12).

BCLMP 0256: This H II region contains three individual metallicity measurements from Rosolowsky & Simon (2008). We adopted the nearest measurement to each H I patch, as can be seen in Table 13. A partial H I ridge surrounding BCLMP 0256 on the basis of surrounding H I patches is shown, among others, in Fig. 22. Addi-

tional UV sources were measured towards the west, where the extra metallicity measurements were available.

Region BCLMP 0650 (Fig. 23; Table 14) shows a rich morphology of a large-scale PDR and intermediate-size PDRs, of which we have analysed five. While the large-scale H I shell is not very dominant, we still attempted to measure its average column density in a rectangular area, finding a total hydrogen density of 18 cm^{-3} .

BCLMP 0269: This region features a lot of recent star formation, scattered over a relatively large area. The distribution of the atomic hydrogen surrounding the young star clusters is reminiscent of a large-scale shell. The average H I column density of this shell is measured along a straight line in Fig. 24 (Table 15). The region includes a CO measurement by Rosolowsky et al. (2003) that we connect to an intermediate-size PDR. We also include a similarly sized PDR on the eastern part of BCLMP 0269, which looks like our typical candidate PDR.

Our Region 42 lies relatively far from the centre of M33, at about 8.6 kpc (Fig. 25 and Table 16). It features a single UV complex at its centre, surrounded by various H I patches that can be used to probe

the underlying GMCs in this candidate PDR. These patches are expected to indicate medium-scale PDRs. The total hydrogen volume densities found in this way range from 6 to about 220 cm^{-3} . Additionally, we attempted to probe the large-scale PDR by averaging the H I column densities along an arc of H I surrounding the central FUV source. This measurement yields a total hydrogen volume density of $n = 70 \text{ cm}^{-3}$. As in M81 and M83, our method points to the presence of GMCs in the outer regions of these galaxies.

3.4 Combined plots

The measurements of the regions with candidate PDRs presented here are consolidated in Fig. 7. The results at full resolution are indicated with the black crosses. The grey boxes in the background are the results at reduced resolution for reference. The filled boxes correspond to the regions investigated at full resolution. Note that one of the regions, BCLMP 0288, is not included, since we only have a larger scale measurement there (see Section 3.3).

The H I plot is a sampling of H I peaks that decline with the galactocentric radius. Close to the centre of M33, the values are high enough to raise worries about H I being optically thick. The values of G_0 decline as well and generally span a range of 0.1–10. The total hydrogen volume densities are remarkably constant in range and values, ranging from approximately 10 to 300 cm^{-3} . The values in the region closest to the centre, CPSDP 0087g, are lower. We noted previously that this region has a particularly high dust content, depressing the densities that we obtain. The high dust

content may also indicate heavy internal extinction for which we did not correct.

As an additional indication of the likelihood of the H I patches being produced by photodissociation, we looked at the source contrast G/G_{bg} . The same results are plotted without the reduced-resolution results in the background. The open circles in Fig. 8 indicate a corresponding source contrast of less than 0.5. These H I patches generally correspond to a lower value of n and a lower value of G_0 . Finally, plotting G_0 and n does not show a clear correlation, although if an actual correlation were present, it would be more pronounced without the CPSDP 0087g sources.

4 DISCUSSION AND CONCLUSIONS

4.1 Resolution effects

Despite the analysis at different resolutions, the resulting cloud densities do not differ from each other, as they are in the same range. This is shown in Fig. 7, where the densities are shown for those regions that are included at both resolutions. The full-resolution data offer the advantage of (partially) resolving the parent GMCs connected to the OB associations with the opportunity to study the behaviour of H I in more detail (Heiner et al. 2009). On the other hand, there is more confusion in the distribution of H II, where the spatial distribution at the reduced resolution makes it easier to identify the H I patches. With the reduced-resolution data presented here,

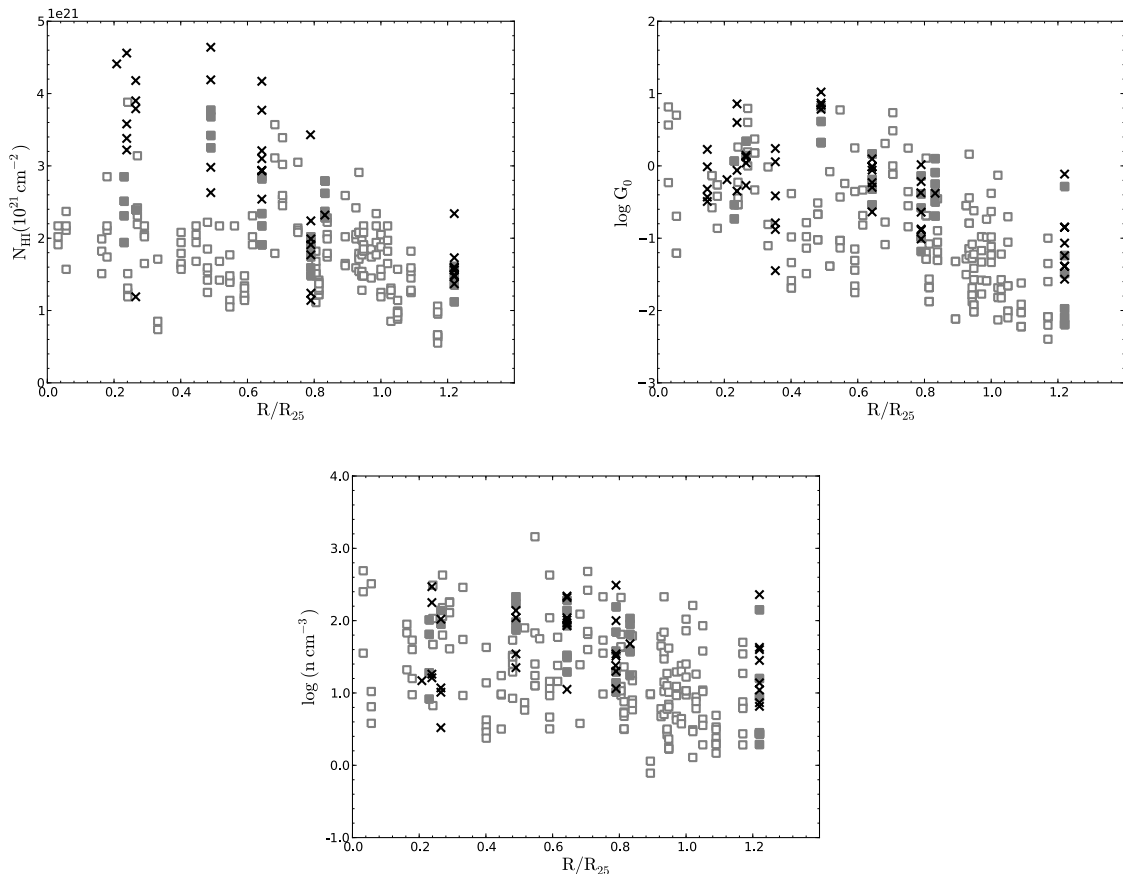


Figure 7. The results of the nine out of 10 candidate PDRs that have detailed results (not the larger scale measurements) are shown here (as crosses): the H I column densities, the incident flux G_0 and the total hydrogen volume densities. The reduced-resolution results are plotted as grey boxes. The filled boxes are the regions with full-resolution result counterparts. Region BCLMP 0288 is not included since it does not feature a discernible detailed morphology.

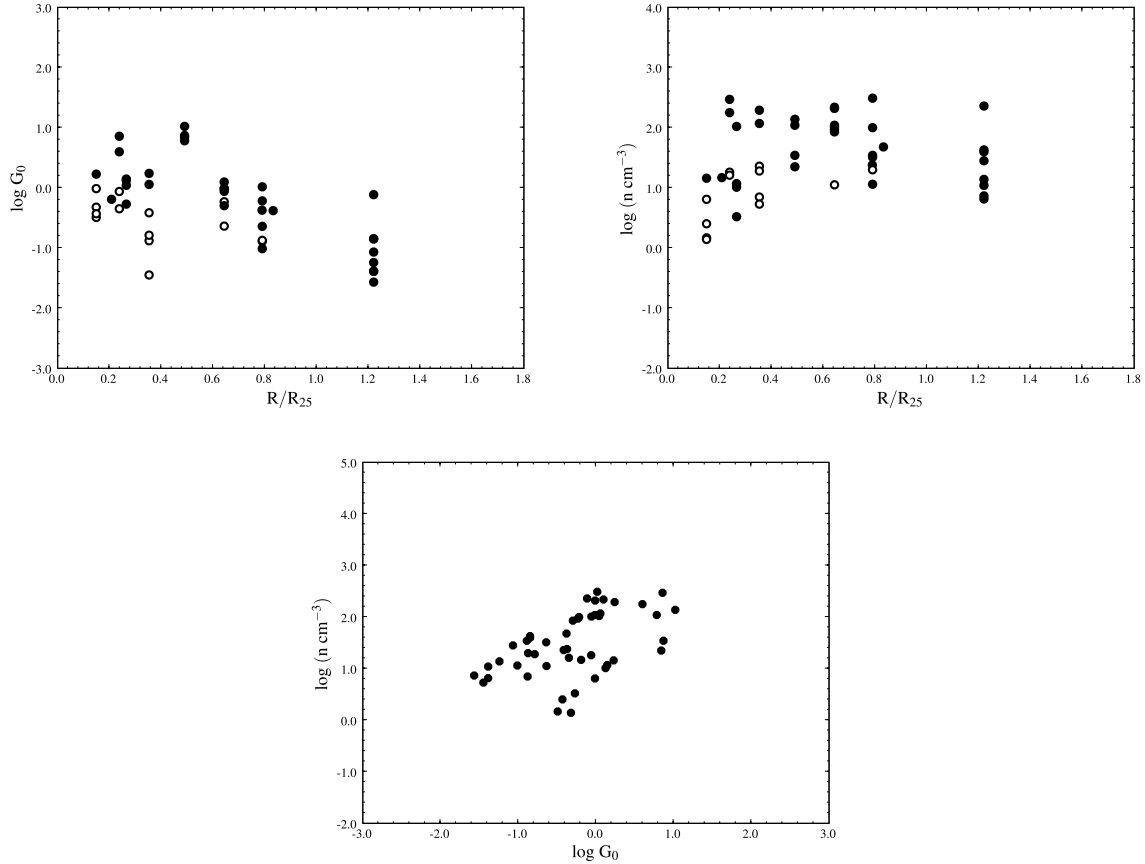


Figure 8. The results of the nine out of 10 regions that have detailed results (not the larger scale measurements) are shown here: the incident flux G_0 , the total hydrogen volume densities and a plot of n versus G_0 . The open circles indicate H I patches with a source contrast below 0.5. Region BCLMP 0288 is not included since it does not feature a discernible detailed morphology.

we were able to study the volume Schmidt law of star formation (Heiner et al. 2009).

Either way, the resulting cloud densities do not differ significantly, and selecting more regions for full-resolution study is not expected to give more insight at this time.

4.2 Performance of the PDR method across M33, M81 and M83

The M81 and M83 results were presented in Heiner et al. (2008a,b). Both galaxies show no clear drop in total hydrogen volume densities out to larger galactocentric radii. In the case of M83, we were able to identify candidate PDRs out to relatively large radii. In the view of photodissociated atomic hydrogen, there is no reason to assume that individual GMC densities change farther away from the galactic centre. In fact, Bigiel et al. (2010) confirm that FUV and H I emission continue to be correlated spatially out to $3R_{25}$ even. At these distances, we would expect PDRs and photodissociated H I to occur just as they would more towards the galactic centre.

We generated boxplots for M81 and reproduced boxplots for M83 for comparison to the M33 results at equivalent resolution. These are shown in Fig. 9. In a box-and-whisker plot, or boxplot, the boxes span the lower to upper quartiles of the data (50 per cent of the data points combined), with a line indicating the median value. The so-called ‘whiskers’ show the range of the data (1.5 times the inner quartile range of points), with outliers plotted individually (+).

The M81 results were recalculated to match certain parameters used in M83 and M33 for consistency, like the solar metallicity and the foreground extinction. A solar metallicity of 8.68 was adopted (Allende Prieto et al. 2001) and the M81 foreground extinction was taken to be 0.63 mag, where 1.37 mag was used in Heiner et al. (2008a). As a result of this, all total hydrogen volume densities derived for M81 used here are a factor of 2 lower than calculated previously.

Finally, the results presented and summarized here are in many ways similar to those of M101 presented by Smith et al. (2000), but cannot be compared directly to our results. They found total hydrogen volume densities in the range of $30\text{--}1000 \text{ cm}^{-3}$. They used UIT data, while newer *GALEX* data have better sensitivity and the UV flux normalization can be expected to be slightly different due to the respective UIT and *GALEX* filter function. The method that was applied to M101 used a different way of measuring the H I column density, since averages of concentric ellipses around the central UV sources were used instead of individual H I patch measurements. While averaging the column densities is expected to yield a lower overall column density, they did not subtract a local or global H I background level. These two differences may balance each other out. Another difference is their assumptions about an internal extinction correction, which we have chosen not to apply due to geometrical considerations (Heiner et al. 2008a).

The first observation that can be made is that there seems to be no fundamental difference between the three galaxies. In all cases,

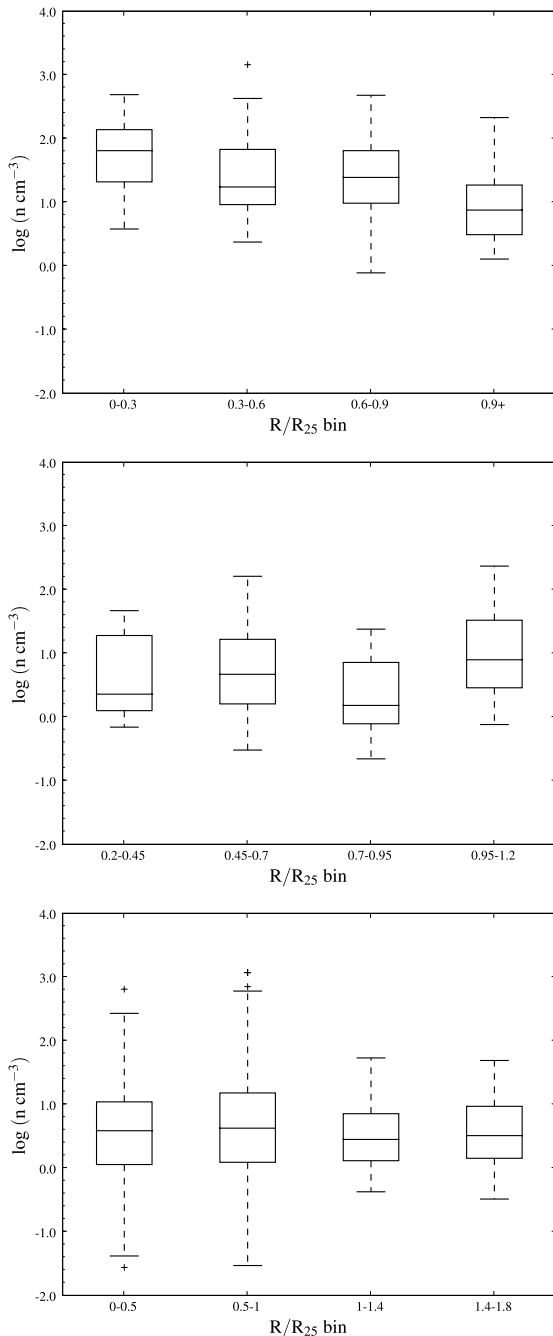


Figure 9. Boxplots showing the range of total hydrogen volume densities in the galaxies M33, M81 and M83, respectively (from the left-hand to right-hand side). The bins have been chosen per galaxy to divide the available range of galactocentric radii into four parts. The M83 results, previously published in Heiner et al. (2008b), show a greater spread in values within R_{25} than the other results. The M33 results are narrower in spread and tend to be higher in total hydrogen volume densities.

we find a range of values that do not change significantly with the galactocentric radius. The lowest cloud densities that we find should not constitute an actual physical limit, since these values are either due to a large separation $\rho_{\text{H I}}$ (where it becomes questionable whether H I is really connected to the central UV source) or possibly pushing the method to the limits of its applicability. The largest cloud densities are a better indication, since the responsible H I patches are generally closer to the central UV source and their

connection is therefore more convincing. The largest densities in M81 are lower than those of M33 and M83. We already speculated in Heiner et al. (2008a) that this is consistent with the fainter levels of CO emission in M81. In the case of M83, they appear to be lower outside the optical disc, but this feature does not show in M33.

4.3 Conclusions

In Heiner et al. (2009), we presented our first findings of total hydrogen volume densities in candidate PDRs in M33 using the PDR method. We used reduced-resolution results to recover the volume Schmidt law of star formation in M33 in Heiner et al. (2010). In this paper, we present the complete results of applying the PDR method to M33. We summarize our findings as follows:

(1) We presented total hydrogen volume densities of candidate PDRs in M33 obtained with the PDR method and compared them with those found in M81 and M83. These PDRs occur throughout the optical discs of these galaxies and beyond. UV emission can be matched to the presence of atomic hydrogen out to the detection limit of 21-cm images.

(2) We find total hydrogen volume densities of candidate PDRs in M33 ranging from 1 to 500 cm^{-3} .

(3) The densities in candidate PDRs of M81 and M83 are in the same range, although the spread in the M83 results is higher, indicating the presence of higher density GMCs in M83. The M33 densities go up to the same level as in M83, although the spread is narrower. The PDR method therefore yields similar results nearby (M33) as well as farther away (M83).

(4) The cloud densities presented here at two different resolutions show that the PDR method yields consistent results that are not significantly affected by resolution effects.

ACKNOWLEDGMENTS

JSH acknowledges support by a CRAQ postdoctoral fellowship. Significant parts of this work were carried out at the Kapteyn Astronomical Institute and the Space Telescope Science Institute funded by the STScI Director's Discretionary Research Fund. Data analysis for this work was done primarily using GIPSY (Groningen Image Processing SYstem) (Ekers, Allen & Luyten 1973; van der Hulst et al. 1992; Vogelaar & Terlouw 2001). We thank the anonymous referee for useful comments that improved this paper.

REFERENCES

- Allen R. J., 2004, in Block D. L., Puerari I., Freeman K. C., Groess R., Block E. K., eds, *Penetrating bars through masks of cosmic dust: the Hubble tuning fork strikes a new note*. Kluwer, Dordrecht, p. 731
- Allen R. J., Atherton P. D., Tilanus R. P. J., 1986, *Nat*, 319, 296
- Allen R. J., Knapen J. H., Bohlin R., Stecher T. P., 1997, *ApJ*, 487, 171
- Allende Prieto C., Lambert D. L., Asplund M., 2001, *ApJ*, 556, L63
- Bigiel F., Leroy A., Seibert M., Walter F., Blitz L., Thilker D., Madore B., 2010, *ApJ*, 720, L31
- Boulesteix J., Courtes G., Laval A., Monnet G., Petit H., 1974, *A&A*, 37, 33
- Braine J. et al., 2010, *A&A*, 518, L69
- Braun R., Thilker D. A., Walterbos R. A. M., Corbelli E., 2009, *ApJ*, 695, 937
- Courtes G., Petit H., Petit M., Sivan J.-P., Dodonov S., 1987, *A&A*, 174, 28

Ekers R. D., Allen R. J., Luyten J. R., 1973, *A&A*, 27, 77
 Engargiola G., Plambeck R. L., Rosolowsky E., Blitz L., 2003, *ApJS*, 149, 343
 Gil de Paz A. et al., 2007, *ApJS*, 173, 185
 Gratier P. et al., 2010, *A&A*, 522, A3
 Heaton H. I., 2009, *ApJ*, 694, 978
 Heiner J. S., Allen R. J., Emonts B. H. C., van der Kruit P. C., 2008a, *ApJ*, 673, 798
 Heiner J. S., Allen R. J., Wong O. I., van der Kruit P. C., 2008b, *A&A*, 489, 533
 Heiner J. S., Allen R. J., van der Kruit P. C., 2009, *ApJ*, 700, 545
 Heiner J. S., Allen R. J., van der Kruit P. C., 2010, *ApJ*, 719, 1244
 Israel F. P., 1997, *A&A*, 328, 471
 Issa M. R., MacLaren I., Wolfendale A. W., 1990, *A&A*, 236, 237
 Lagrois D., Joncas G., 2009, *ApJ*, 700, 1847
 Langer W. D., Velusamy T., Pineda J. L., Goldsmith P. F., Li D., Yorke H. W., 2010, *A&A*, 521, L17
 Leroy A., Bolatto A., Stanimirovic S., Mizuno N., Israel F., Bot C., 2007, *ApJ*, 658, 1027
 Leroy A. K. et al., 2009, *ApJ*, 702, 352
 Magrini L., Vilchez J. M., Mampaso A., Corradi R. L. M., Leisy P., 2007, *A&A*, 470, 865
 Magrini L., Stanghellini L., Corbelli E., Galli D., Villaver E., 2010, *A&A*, 512, A63
 Onodera S. et al., 2010, *ApJ*, 722, L127
 Rosolowsky E., Simon J. D., 2008, *ApJ*, 675, 1213
 Rosolowsky E., Engargiola G., Plambeck R., Blitz L., 2003, *ApJ*, 599, 258
 Rosolowsky E., Keto E., Matsushita S., Willner S. P., 2007, *ApJ*, 661, 830
 Saha A., Thim F., Tammann G. A., Reindl B., Sandage A., 2006, *ApJS*, 165, 108
 Schlegel D. J., Finkbeiner D. P., Davis M., 1998, *ApJ*, 500, 525
 Smith D. A., Allen R. J., Bohlin R. C., Nicholson N., Stecher T. P., 2000, *ApJ*, 538, 608
 Sternberg A., 1988, *ApJ*, 332, 400

van der Hulst J. M., Terlouw J. P., Begeman K. G., Zwitter W., Roelfsema P. R., 1992, in Worrall D. M., Biemesderfer C., Barnes J., eds, *ASP Conf. Ser. Vol. 25, Astronomical Data Analysis Software and Systems I*. Astron. Soc. Pac., San Francisco, p. 131
 van Dishoeck E. F., Black J. H., 1988, *ApJ*, 334, 771
 Vila Costas M. B., Edmunds M. G., 1992, *MNRAS*, 259, 121
 Vogelaar M. G. R., Terlouw J. P., 2001, in Harnden F. R., Jr, Primini F. A., Payne H. E., eds, *ASP Conf. Ser. Vol. 238, Astronomical Data Analysis Software and Systems X*. Astron. Soc. Pac., San Francisco, p. 358
 Wilson C. D., Scoville N., 1992, *ApJ*, 385, 512
 Zaritsky D., Elston R., Hill J. M., 1989, *AJ*, 97, 97

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 5. Locations and FUV fluxes of candidate PDRs.

Table 6. Candidate PDR results.

Tables 7–16. Detailed measurements for CPSDP 0087g, CPSDP Z204, NGC 595, BCLMP 0695, NGC 604, BCLMP 0288, BCLMP 0256, BCLMP 0650, BCLMP 0269 and Region 42.

Figures 10–15. M33 sources 1–42.

Figures 16–25. Images and finding charts for CPSDP 0087g, CPSDP Z204, NGC 595, BCLMP 0695, NGC 604, BCLMP 0288, BCLMP 0256, BCLMP 0650, BCLMP 0269 and Region 42.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.